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# Spin Transfer in Inclusive $\Lambda^0$ Production by Transversely Polarized Protons at 200 GeV/$c$

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# Abstract

Surprisingly large polarizations in hyperon production have been known for a long time. The spin dynamics of the production process can be further investigated with polarized beams. Recently, a negative asymmetry $A_N$ was found in inclusive $\Lambda^0$ production with a 200 GeV/$c$ transversely polarized proton beam. The depolarization $D_{NN}$ in $p \uparrow + p \rightarrow \Lambda^0 + X$ has been measured with the same beam over a wide $x_F$ range and at moderate $p_T$. $D_{NN}$ reaches positive values of about 30 % at high $x_F$ and $p_T \sim 1.0$ GeV/$c$. This result shows a sizeable spin transfer from the incident polarized proton to the outgoing $\Lambda^0$.


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The observation 20 years ago of a large negative polarization in inclusive $\Lambda^0$ production by an unpolarized proton beam at 300 GeV/c [1] renewed interest in spin as an important factor in high-energy hadron interactions. Afterwards several experiments measured large polarizations for various hyperons over a wide kinematical range [2]. Previous expectations, based on Regge theory and QCD predictions, were that spin effects would vanish at high energies, since the smallness of spin-flip amplitudes and the contribution of several production channels to an inclusive process with large multiplicity of final states make it unlikely to have the coherent interference between spin non-flip and spin flip amplitudes that leads to sizeable polarization effects. Recently, a significant negative analyzing power $A_N$ has been found at 200 GeV/$c$ in inclusive $\Lambda^0$ production by a transversely polarized proton beam at high $x_F$ and moderate $p_T$ ($p_T \sim 1$ GeV/$c$) [3]. Large $A_N$ values have been also found in inclusive pion production with the same proton and antiproton polarized beam [4,5].

Different quark-parton models using static SU(6) wave functions were proposed to interpret these polarization effects by introducing a spin dependence into the partonic fragmentation and recombination processes [6–8]. The $\Lambda^0$ polarization is attributed to some mechanism, based on semiclassical arguments [6,7] or inspired to QCD [8], by which *strange* quarks produced in the fragmentation process acquire a large negative polarization. The features of the pion $A_N$ data [4,5] are compatible with these models, provided that this effect occurs also for *up* and *down* quarks. The spin dynamics of these processes can be further investigated using polarized proton beams. In the previous models no correlation with the incident proton polarization is expected in inclusive $\Lambda^0$ production, since the $\Lambda^0$ spin is carried entirely by its constituent *strange* quark and the *ud* di-quark (which is in a spin and isospin singlet state) propagates unperturbed as a spectator in the interaction. Therefore spin asymmetries related to the beam polarization are expected to vanish. The negative asymmetry $A_N$ observed in $\Lambda^0$ production [3] is difficult to integrate in this picture unless the spectator *ud* di-quarks play a more significant role in the recombination process than generally expected [9]. Studies of other spin asymmetries in high energy hyperon production add further input to understand these phenomena.

In this Letter we report on the measurement of the depolarization parameter $D_{NN}$ in inclusive $\Lambda^0$ production with the 200 GeV/$c$ Fermilab polarized proton beam [10] and a 1.0 meter long liquid hydrogen target in the kinematical range $0.2 \leq x_F \leq 1.0$ and $0.1 \leq p_T \leq 1.5$ GeV/$c$. The double-spin parameter

$$D_{NN} \;=\; \frac{E\frac{d^3\sigma}{dp^3}^{\uparrow\uparrow} - \; E\frac{d^3\sigma}{dp^3}^{\uparrow\downarrow}}{E\frac{d^3\sigma}{dp^3}^{\uparrow\uparrow} + \; E\frac{d^3\sigma}{dp^3}^{\uparrow\downarrow}}$$

measures the fraction of the incident proton polarization transferred to the inclusively produced $\Lambda^0$. $E\frac{d^3\sigma}{dp^3}^{\uparrow\uparrow\,(\uparrow\downarrow)}$ is the spin-dependent differential cross-section for the process $p\uparrow + \; p \rightarrow \Lambda^0 \uparrow + \; X$ with parallel (anti-parallel) spin configurations for the incident proton and the outgoing $\Lambda^0$, both polarizations being orthogonal to the production plane.

The transversely polarized proton beam contained simultaneously protons of opposite *tagged* polarizations. This considerably suppressed systematic effects. The average beam polarization was $0.46 \pm 0.03$ for both signs. Typical beam intensities at the experimental target were of the order of $2{\times}10^7$ polarized protons per 20 second spill.

$\Lambda^0$ hyperons produced at the experimental target were identified by reconstructing their decay $\Lambda^0 \rightarrow p\pi^-$. Charged particles were measured in a forward spectrometer, described in Refs. [3,4], equipped with 42 multi-wire proportional planes and a 3 T-m $\int Bdl$ dipole analyzing magnet. A threshold Cherenkov counter, C1, downstream of the magnet, was used for proton identification.

Secondary $\Lambda^0$ decay vertices ($V^0$'s) were searched by combining proton tracks identified by C1 with negatively charged tracks assuming that they were $\pi^-$'s [3]. It was required that: (1) the closest distance in space of the two tracks was $< 2$ mm and that the $V^0$ decay vertex was located between 20 cm and 540 cm downstream of the target end; (2) the $V^0$ came from the target and matched there the beam impact point within 2 mm in the transverse plane; (3) the $V^0$'s populated the decay phase space region corresponding to $\Lambda^0$ decays, bounded by $0.45 < (p_L^+ - p_L^-)/(p_L^+ + p_L^-) < 0.95$ and $q_T = q_T^+ = q_T^- < 0.12$ GeV/$c$, where $p_L^+$ ($p_L^-$) is the longitudinal component of the positive (negative) track momentum and $q_T$ is the transverse component of these momenta with respect to the $V^0$ line of flight.

These selection cuts led to a clean $\Lambda^0$ peak in the $p\pi^-$ invariant mass spectrum, centered at 1.116 GeV/$c^2$ with a width $\sigma = 1.7$ MeV/$c^2$ and an estimated 2 % uniform background below the $\Lambda^0$ peak, as most sources of background were suppressed by the vertex fiducial volume cut, the selection of the $\Lambda^0$ decay phase space region, and $K_S^0 \to \pi^+\pi^-$ decays were rejected by C1. We selected $\Lambda^0$'s in a mass window of $\pm 5.1$ MeV/$c^2$ about the peak. For the $D_{NN}$ analysis we required additionally that the $\Lambda^0$'s were produced to the beam right in the azimuthal angular interval of $\pm 60°$ from the horizontal plane around the beam axis. A sample of about 40,000 $\Lambda^0$'s was thus selected.

For each $x_F$ and/or $p_T$ bin, the double-spin parameter $D_{NN}$ was extracted from the $\Lambda^0$ decay proton angular distribution in the $\Lambda^0$ rest frame by defining 4 sets of events, integrating the decay proton angular distribution above and below the $\Lambda^0$ production plane for the two opposite beam polarizations separately. $D_{NN}$ is then obtained from the asymmetry:

$$D_{NN} \;=\; \frac{1}{P_B \langle \cos\phi_V \rangle} \, \frac{2}{\alpha_\Lambda} \, \frac{\left(N^+_{up} + N^-_{down}\right) - \left(N^-_{up} + N^+_{down}\right)}{\left(N^+_{up} + N^-_{down}\right) + \left(N^-_{up} + N^+_{down}\right)}$$

where, for instance, $N^+_{up}$ is the number of $\Lambda^0$'s produced by beam protons polarized upward and emitting decay protons in the positive hemisphere with respect to the normal to the production plane. $P_B$ is the proton beam polarization, $\phi_V$ is the angle between the beam polarization axis directed upward and the normal to the production plane ($\langle \cos\phi_V \rangle \approx -0.85$ in the selected azimuthal range), and $\alpha_\Lambda = 0.642$ is the $\Lambda^0$ decay asymmetry.

The $D_{NN}$ results thus obtained, are independent, to a good accuracy, of apparatus and reconstruction biases, since $\Lambda^0$'s were measured with the same apparatus and opposite beam polarizations simultaneously. For a check of systematic biases we evaluated $D_{NN}$ for non-$\Lambda^0$ events ($p\pi^-$ combinations outside of the $\Lambda^0$ mass window and $K_S^0$), and we found that $D_{NN} = 0.007 \pm 0.039$ for these background events. We also evaluated the $\Lambda^0$ polarization by averaging over opposite beam polarizations and found a good agreement with existing polarization results.

The depolarization $D_{NN}$ is given in Table 1 and shown in Figure 1 as a function of $p_T$ averaged over the $x_F$ interval of 0.2–1.0. $D_{NN}$ increases with $p_T$ to significantly large positive values with an indication of flattening in $p_T$ above 1.0 GeV/$c$, while at low $p_T$ values it is compatible with zero. Figure 2 and Table 2 show the double-spin parameter $D_{NN}$ as a function of $x_F$ averaged over the $p_T$ interval of 0.1–1.5 GeV/$c$. At large $x_F$ values $D_{NN}$ reaches positive values as large as 30 % at $p_T \sim 1$ GeV/$c$ (see also Table 1 rows 6–11, where the $p_T$ dependence is shown for two separate $x_F$ intervals), while almost no dependence in $x_F$ is observed for $x_F < 0.6$, where $D_{NN}$ is compatible with zero or slightly positive. In Figure 3 the $D_{NN}$ data are split into two $p_T$ intervals and plotted as a function of $x_F$. At low $p_T$ they appear to be essentially zero, while in the high $p_T$ bin they show large positive values. A few $D_{NN}$ measurements in inclusive $\Lambda^0$ production were previously performed with polarized proton beams at much lower energies of 6 GeV/$c$ [11], 13.3 GeV/$c$ and 18.5 GeV/$c$ [12]. Figure 2 shows also data obtained at 18.5 GeV/$c$ for a bin about $\langle p_T \rangle \sim 1.0$ GeV/$c$ [12]. These data appear to be compatible with zero over the measured range, which however doesn't extend above $x_F \sim 0.5$. More recently, a sizeable spin transfer has been inferred in $\Omega^-$ production by high energy neutral beams containing transversely polarized $\Lambda^0$'s and $\Xi^0$'s [13].

The kinematical dependence of present $D_{NN}$ results shows, in magnitude, a behavior similar to the hyperon polarization [2]. The observed $D_{NN}$ results, as in the case of the $A_N$ data in inclusive $\Lambda^0$ production [3], cannot however be directly obtained from a mechanism such as proposed to explain the $\Lambda^0$ polarization [6–8], where a highly polarized *strange* quark produced in the fragmentation process recombines with an unpolarized *ud* spectator di-quark from the incident proton independently of its polarization. Our results indicate a substantial spin transfer from the incident polarized proton to the inclusively produced $\Lambda^0$ as large as 30 % at high $x_F$ ($x_F > 0.6$) and $p_T \sim 1$ GeV/$c$.

More recent models based on non-perturbative approaches and peripheral mechanisms with an underlying quasi-binary subprocess, such as a $\pi$ exchange mechanism [14], or resonance-decay interference between real and virtual channels [15], were proposed to explain the $\Lambda^0$ polarization. These models might also accomodate a more substantial spin dependence in the $\Lambda^0$ production process, such as the one shown by the present data. A model, based on the idea of rotating constituents in polarized protons [16], is fairly successful in accounting for the observed $A_N$ behavior in pion production. This model appears to reproduce qualitatively also the $\Lambda^0$ analyzing power and the $D_{NN}$ data presented in this Letter.

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## TABLES

TABLE I. $D_{NN}$ data for $p\uparrow + p \to \Lambda^0 + X$ as a function of $p_T$ (the errors are statistical only; systematic errors were estimated to be negligible compared to statistical ones).

| $p_T$ interval (GeV/$c$) | $D_{NN}$ | $\langle x_F \rangle$ | $\langle p_T(\mathrm{GeV}/c)\rangle$ |
|---|---|---|---|
| | $0.2 \leq x_F \leq 1.0$ | | |
| 0.1–0.3 | $-0.05 \pm 0.12$ | 0.42 | 0.23 |
| 0.3–0.5 | $-0.035 \pm 0.074$ | 0.49 | 0.41 |
| 0.5–0.7 | $0.147 \pm 0.071$ | 0.56 | 0.60 |
| 0.7–1.0 | $0.216 \pm 0.081$ | 0.61 | 0.82 |
| 1.0–1.5 | $0.26 \pm 0.17$ | 0.66 | 1.13 |
| | $0.2 \leq x_F \leq 0.5$ | | |
| 0.1–0.4 | $-0.03 \pm 0.10$ | 0.38 | 0.29 |
| 0.4–0.6 | $0.14 \pm 0.11$ | 0.40 | 0.49 |
| 0.6–1.0 | $0.20 \pm 0.13$ | 0.42 | 0.74 |
| | $0.5 \leq x_F \leq 1.0$ | | |
| 0.5–0.7 | $0.09 \pm 0.09$ | 0.65 | 0.60 |
| 0.7–1.0 | $0.24 \pm 0.09$ | 0.67 | 0.82 |
| 1.0–1.5 | $0.31 \pm 0.18$ | 0.69 | 1.14 |

TABLE II. $D_{NN}$ data for $p\uparrow + p \to \Lambda^0 + X$ as a function of $x_F$ (the errors are statistical only).

| $x_F$ interval | $D_{NN}$ | $\langle x_F \rangle$ | $\langle p_T(\mathrm{GeV}/c)\rangle$ |
|---|---|---|---|
| | $0.1 \leq p_T \leq 1.5$ GeV/$c$ | | |
| 0.20–0.35 | $0.03 \pm 0.13$ | 0.30 | 0.41 |
| 0.35–0.45 | $0.039 \pm 0.093$ | 0.40 | 0.49 |
| 0.45–0.55 | $0.079 \pm 0.082$ | 0.50 | 0.57 |
| 0.55–0.65 | $0.081 \pm 0.085$ | 0.60 | 0.64 |
| 0.65–0.80 | $0.148 \pm 0.086$ | 0.71 | 0.71 |
| 0.80–1.0 | $0.35 \pm 0.16$ | 0.85 | 0.79 |
| | $0.1 \leq p_T \leq 0.6$ GeV/$c$ | | |
| 0.2–0.4 | $-0.05 \pm 0.11$ | 0.33 | 0.37 |
| 0.4–0.6 | $0.01 \pm 0.08$ | 0.49 | 0.42 |
| 0.6–0.8 | $-0.02 \pm 0.11$ | 0.68 | 0.47 |
| | $0.6 \leq p_T \leq 1.5$ GeV/$c$ | | |
| 0.3–0.5 | $0.17 \pm 0.12$ | 0.43 | 0.77 |
| 0.5–0.7 | $0.19 \pm 0.09$ | 0.60 | 0.81 |
| 0.7–1.0 | $0.37 \pm 0.11$ | 0.79 | 0.84 |

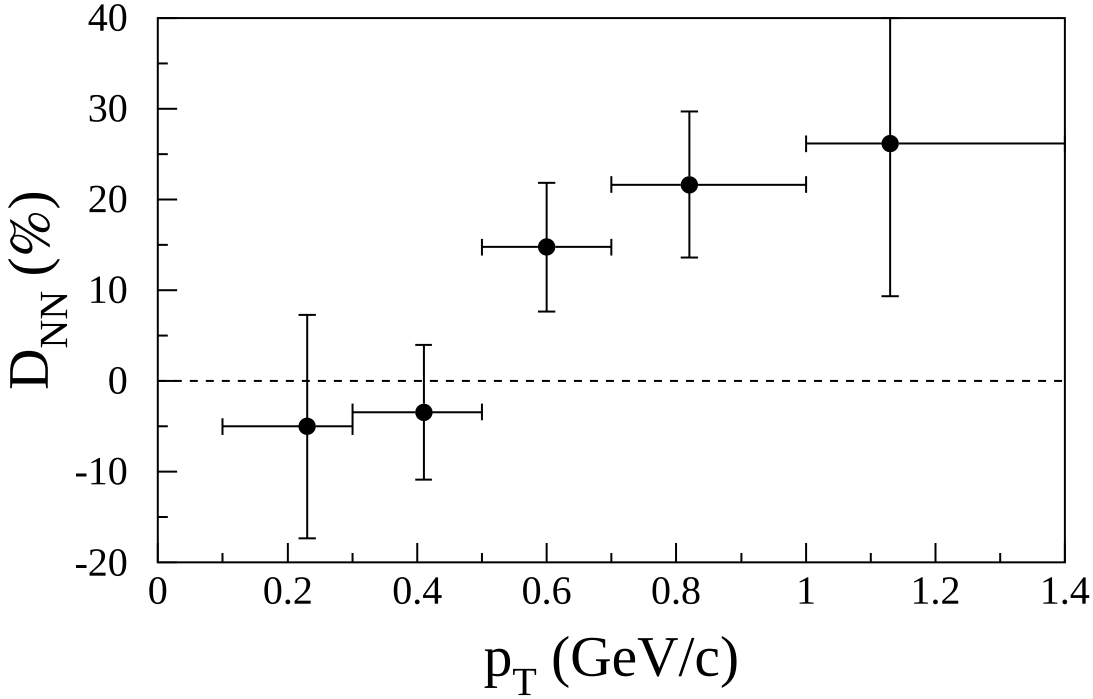


FIG. 1. $D_{NN}$ data as a function of $p_T$.

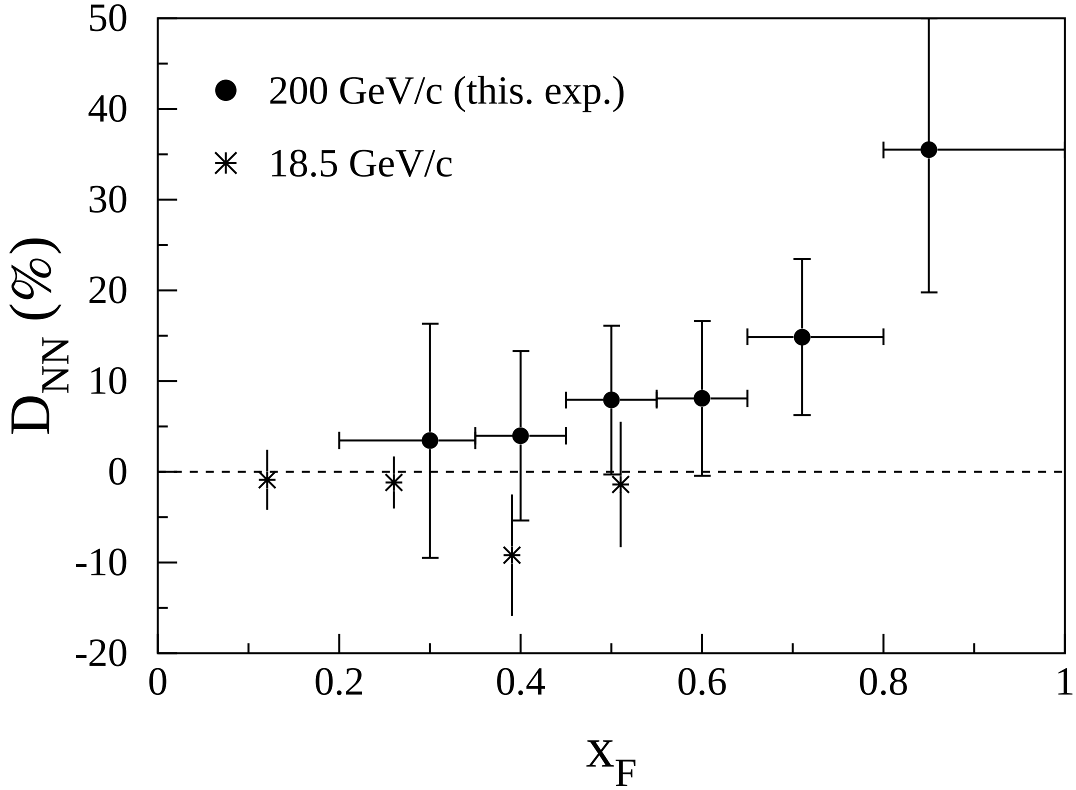


FIG. 2. $D_{NN}$ data as a function of $x_F$. Also shown are $D_{NN}$ measurements at 18.5 GeV/$c$ from Ref. [12] ($\langle p_T \rangle \sim 1.0$ GeV/$c$ for the plotted points).

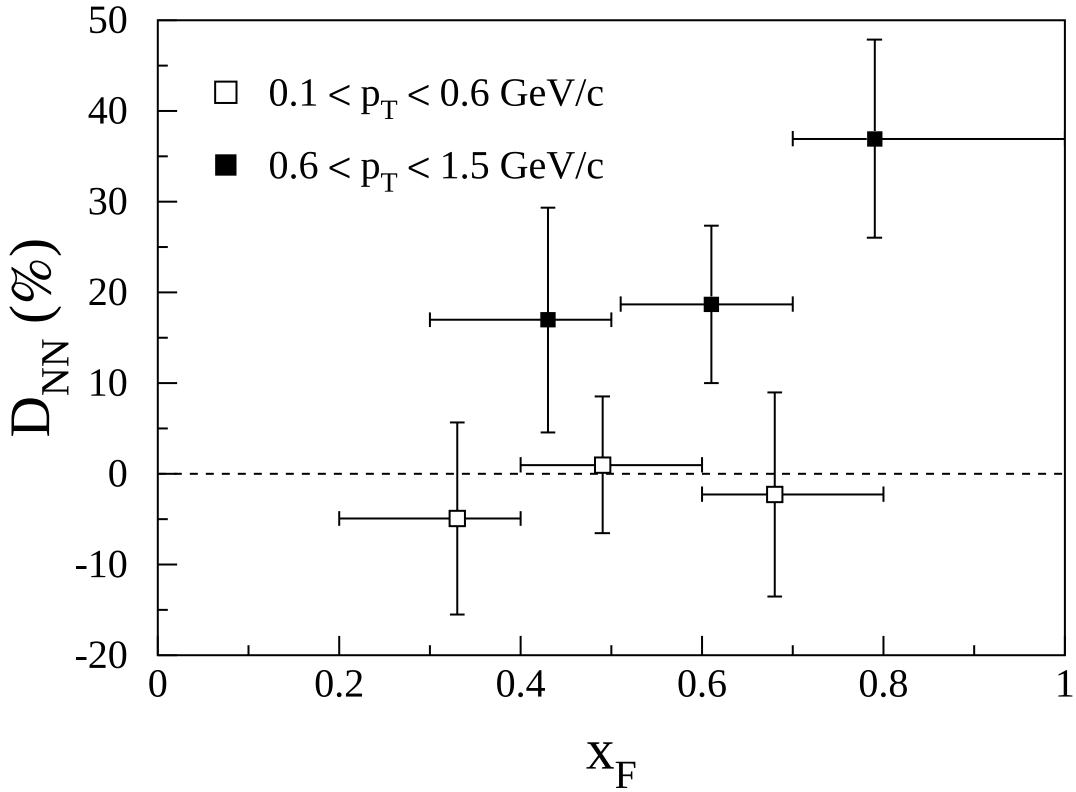


FIG. 3. $D_{NN}$ data as a function of $x_F$ divided into two $p_T$ intervals of $0.1 \leq p_T \leq 0.6$ GeV/$c$ (open squares) and $0.6 \leq p_T \leq 1.5$ GeV/$c$ (full squares).